Present Relative Sea Level Rise in the Northern Adriatic Coastal Area

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Abstract

Relative sea level rise (RSLR), that has been occurred along the entire coastal areas of the Northern Adriatic Sea, includes land subsidence, both natural and man-induced, and eustacy. Their combined effect has produced relative ground settlements ranging from centimetres to meters. RSLR represents one of the geologic hazards threatening the low-lying coast. Recent progresses made in understanding these two processes are presented. Synthetic Aperture Radar (SAR) interferometry has significantly improved the knowledge of actual land subsidence. In particular, comprehensive maps of the vertical displacements occurred over the period 1992-2009 in the region between Venice and Ravenna reveal a significant spatial variability, ranging from a slight 1 to 2 $\text{mm}\cdot\text{yr}^{-1}$ uplift, to a serious subsidence of more than 15 $\text{mm}\cdot\text{yr}^{-1}$. The availability of tide gauge data in Trieste, Venice, and Ravenna allows accurate assessment and meaningful observations on sea level change. The period 1896-2006 is characterized by an average rise of 1.2 ± 0.1 $\text{mm}\cdot\text{yr}^{-1}$. The analyses here performed show that a time series at least 50 yr long must be used to obtain statistically significant results and reliable trend, due to the 7-8 year pseudo-cyclicity, recorded at many Mediterranean coastal stations. In Venice and Ravenna the influence of land subsidence on the RSLR amounts to 57% and 85%, respectively. This percentage has been estimated in 95% at the Po Delta.

1 Introduction

The Northern Adriatic (NA) Sea is characterized by a shallow water depth and a subsiding sedimentary basin underlies its western side (Figure 1). The Italian coastland is characterized by low-lying environments such as deltas, lagoons, wetlands, and farmlands subjected to a marked anthropogenic impact and at great hydrogeological risk. The relative sea level rise (RSLR), i.e. the interaction between land subsidence and eustacy, has been responsible for significant changes in coastal morphology over millennia, and is still today one of the major environmental hazards. The NA coastland developed after the last glacial maximum during the Holocene transgression and from about 5,000 yr BP, over highstand times, the coastline began to prograde seaward due to the sediment supply from major rivers, and delta and lagoon systems developed. During the last millennium, the NA coastland has been even more affected by anthropogenic impacts. The formation of the modern deltaic system of Po River dates back to about 500 yr BP. In general the whole coast reached the

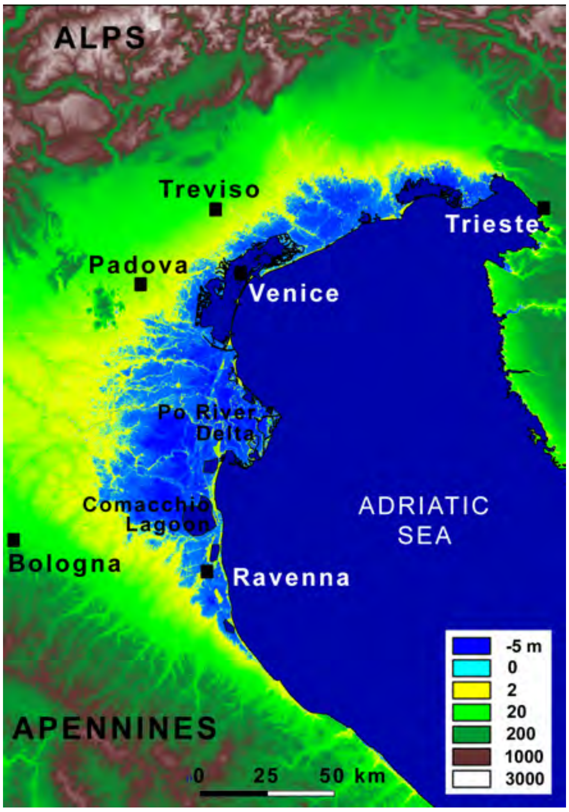

Figure 1: DEM of the NA region with the location of the most important cities. The coastland lying below the m.s.l. is highlighted by the blu-scale colour.

present setting only a couple of centuries ago under the strong influence of human interventions [5, 6].

Man-induced land subsidence has greatly affected the NA coastland over the 20th century, and especially after World War II, when overexploitation of subsurface fluids was responsible for a general lowering of the coastal plain and a significant coastline retreat [7, 8]. After the 1960s-1970s, when the relationships between land settlement and fluid withdrawal clearly emerged, the drastic reduction of the pumping rates produced a significant decrease of the subsidence rates. However, land subsidence is a process that is still affecting the study area. Rise of the sea level during the 20th century and at present is a well documented process worldwide that is linked to climate changes, mainly ice melting and the consequent variation in the mass and volume of the oceans. The relatively modest warming recorded throughout the last century has however induced global rises of sea level that have approached 1.2-2.0 mm$\cdot$yr^{-1} [9]. In this respect, it is important to point out that the comparison between long tide-gauge records around

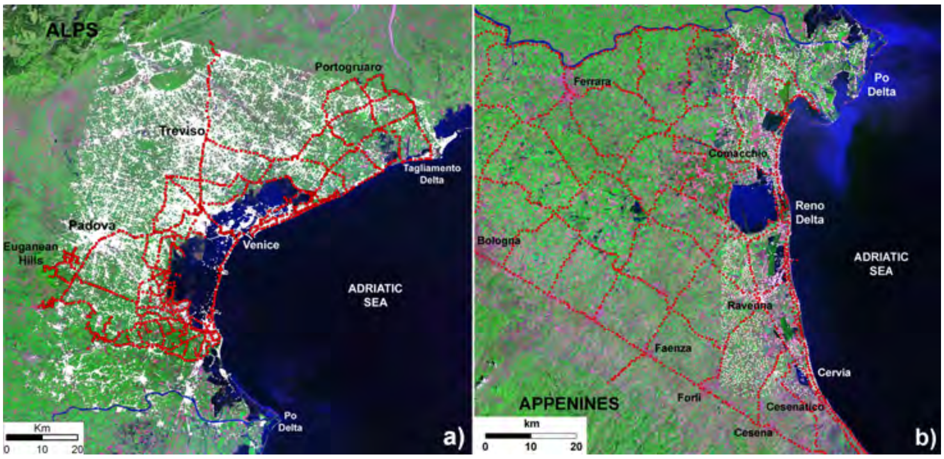

Figure 2: Land subsidence monitoring networks in the a) Venetian, and b) Emilia-Romagna costal plains. White dots represent the position of the persistent scatterers detected by PSI on ERS-1/2 acquisitions and the red dots are the location of the levelling benchmarks. The information are provided after [1] and [2] for the Venice region and after [3] and [4] in Emila-Romagna.

the world shows an eustatic rate in the NA Sea, along with the whole Mediterranean Sea, significantly lower (by approximately 35%) than the global mean value. This is likely due to Northern Atlantic Oscillation (NAO)-induced changes in atmospheric pressure, temperatures, and salinity variation, on account also of the specific features of this almost closed sea (e.g., [10]).

In this work we investigate the present RSLR by using Synthetic Aperture Radar (SAR)-based interferometry and long and nearly continuous tide gauge records that allow to separate the two components, i.e. vertical land movements and eustacy, respectively.

2 Data and methods

Levelling surveys, though not made on a regular basis, have been periodically carried out in the NA coastland since the end of the 19th century. Significant enlargement of the levelling networks has been carried over the last 20 yr in the areas characterized by the stronger land sinking. Global Positioning System (GPS) has been used to monitor vertical movements mostly from the 1990s when GPS measurements reached a millimetre-level accuracy.

Differential and Continuous Global Positioning System (DGPS and CGPS) surveys have then been extensively used to complement the ground-based surveys.

Furthermore, land subsidence monitoring has been significantly improved over the last couple of decades by space-borne earth observation techniques based on SAR interferometry. The measurements were initially carried out by the DInSAR approach [11] and more recently by Persistent Scatterer Interferometry (PSI) [12].

Recently, SAR-based interferometry has been widely adopted in the NA coastland. Two classes of PSI process i.e., the Permanent Scatterers (PS) (e.g., [13]) and the Interferometric Point Target Analysis (IPTA) (e.g., [14]), have significantly improved the knowledge of the land movements for the areas North and South of the Po River, respectively. Levelling and GPS measurements have been processed with the main purpose of calibrating the SAR surveys (Figure 2).

Here we present the PSI results obtained with the following satellite images:

- ERS-1/2 satellites: available scenes are acquired on a 100×100 km^2 area with a 35-day frequency. The images have been processed to map the movements occurred in the whole coastland from 1992 to 2002 [13, 15, 3, 1, 16, 17, 4];
- ENVISAT satellite: available scenes are acquired on a 100×100 km^2 area with a 35-day frequency. The images have been analyzed to monitor the recent coastland displacements from the northern portion of the Po River delta to the Tagliamento River between 2003 and 2007 [16] ;
- TerraSAR-X satellite: available scenes are acquired on a 30×60 km^2 area with a 11-day frequency. The images acquired from March 2008 to February 2009 have been used to measure the present ground movements along the littoral strips of the Venice Lagoon [18].

Concerning the sea level observation, we analyze the tide gauge measurements from the Trieste, Venice, and Ravenna stations. The available records span the period between 1896 and 2006 (Regione Emilia Romagna, 1996, [19]).

3 Relative sea level rise

RLSL is due to the superposition of natural land subsidence, anthropogenic land subsidence, and eustacy. The separation of each contribution is a difficult task and an accurate computation at a regional/local scale is possible for the last century over which data are available from regular instrumental records. In fact, from the beginning of 1900 spirit levelling and, presently GPS and SAR have been used to survey land elevation. Moreover, starting from the end of 1800 tide-gauge has been adopted to monitor sea level height.

3.1 Land subsidence: an overview

Vertical displacements in the NA coastal areas are caused by both natural and anthropogenic factors. Their understanding is essential to estimate land loss or gain and, consequently, predict the relative sea level changes. Natural and anthropogenic components act on different timescales (millions to thousands years and hundreds to tens years, respectively), reflecting the geological history and the human development of the territory. The role played by the long-term natural causes, i.e. tectonics and glacio-isostasy, is negligible in modern times, while natural compaction of recent alluvial fine-grained deposits has assumed a major importance. As a general statement, a certain correlation exists between the thickness of the Quaternary formations and the amount of natural subsidence, so that the sinking rate exhibits a non-uniform space distribution [20]. Natural land subsidence occurred and continues to occur unevenly at different rates. In particular it has been estimated in the range of 0.5-1.0 $mm \cdot yr^{-1}$ in the Venetian territory

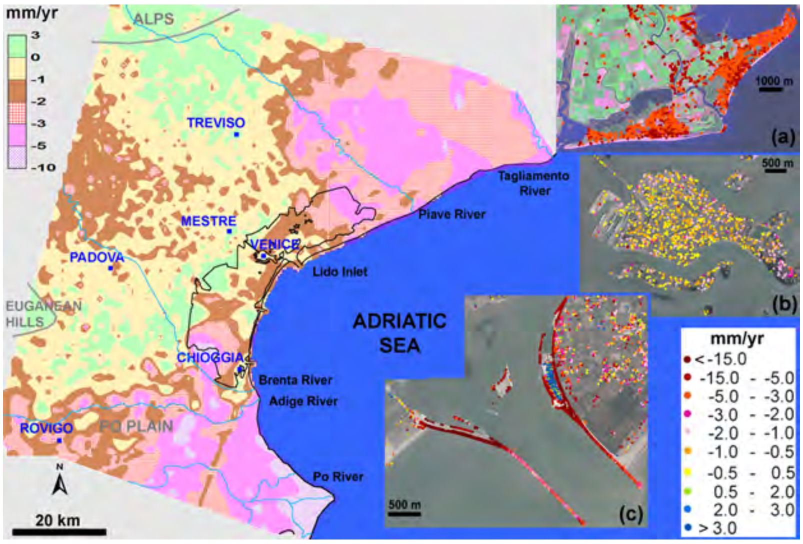

Figure 3: Map of the average displacement rates (mm·yr^{-1}) in the Venice region over the decade 1992-2002 (after [8, 1] and [31]). Negative values mean subsidence and positive uplift. The insets detail the displacements at: a) the Tagliamento river mouth from 2003 to 2007, b) the city of Venice from 1992 to 2000, and c) the Lido inlet from March 2008 to February 2009, obtained by IPTA on ENVISAT, ERS-1/2 and TerraSAR-X scenes, respectively.

(e.g., [21, 22]), about 2.0-2.5 mm·yr^{-1} in the Ravenna area (e.g., [23, 8]), and twice as much in the Po River delta (e.g., [24, 25]). Anthropogenic subsidence due to subsurface fluid withdrawal become a key problem for the land stability over the 20th century, and especially after World War II, when the civil, industrial, agricultural, and tourist development required huge amounts of water and an increasing energy supply. Different fluids were withdrawn along the study coastland: groundwater in the Venice area, gas-bearing water in the Po Delta, and both freshwater from confined aquifers and gas from deep reservoirs in the Ravenna region. Levelling surveys have shown that the cumulative subsidence has reached values of some centimetres in the Venice area [26], 2-3 m in the Po River delta [27, 28, 29], and as much as 1.5 m southward along the Romagna coastland (e.g., [3, 30]). The largest settlement rates of 17 mm·yr^{-1}, 300 mm·yr^{-1}, 110 mm·yr^{-1} were recorded at Venice-Marghera, Po Delta, and Ravenna industrial zone, over the periods 1968-1969, 1950-1957, and 1972-1973, respectively. From the early 1960s, in the Po delta area, and 1970s in the another places, countermeasures have been taken and anthropogenic subsidence strongly reduced or stopped.

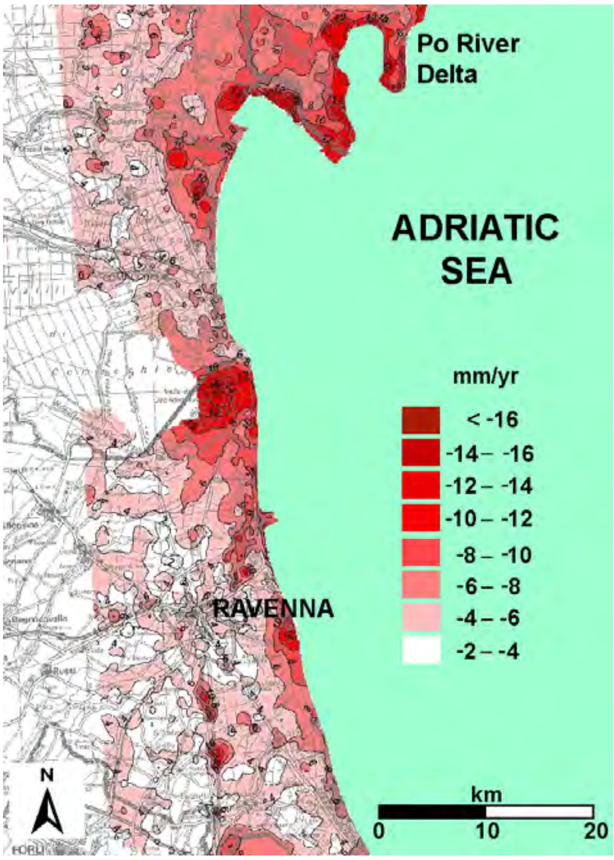

Figure 4: Map of the displacement rates (mm·yr^{-1}) in the Emilia Romagna coastland obtained by PS analysis over the 1992-2000 period using ERS-1/2 images (after [17, 4]).

3.2 Land subsidence: recent quantification

The SAR-based techniques have allowed to map the land subsidence, which is currently affecting the Northern Adriatic coastland, with high accuracy and spatial detail. The result exhibits a resolution never obtained before.

An innovative Subsidence Integrated Monitoring System (SIMS), which efficiently merges the different displacement measurements obtained by levelling, GPS, and SAR-based interferometry, has been designed to accurately and reliably keep land movements under control in the Venice coastland from the Po River to the South to the Tagliamento River northward [1]. Using the ERS-1/2 images acquired between 1992 and 2002, the SIMS provides a comprehensive map of the ground vertical displacements in the Venice region (Figure 3), and shows that, as observed in other coastlands, their movement rates

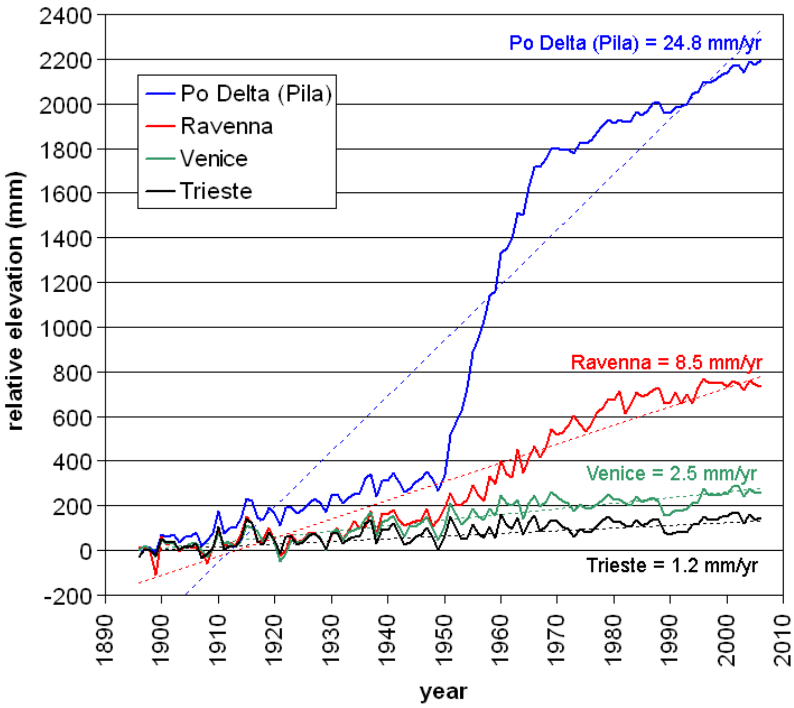

Figure 5: Mean sea level at Trieste, Venice, and Ravenna from 1896 to 2006. The linear regressions of the yearly values are represented together with the average eustatic rate. Ravenna records have been updated after Regione Emilia Romagna (1996). Venice and Trieste records after [32]. The Po Delta time series has been reconstructed as described in the text.

are highly variable. General land stability has been detected in the central part of the study area, including the major cities of Venice, Padova, and Treviso, with scattered local bowls of subsidence of up to 2 to 3 mm$\cdot$yr^{-1}. Conversely, land settlement has appeared as a widespread phenomenon in the northern and southern coastlands and at the lagoon extremities, with rates of up to 5 and 15 mm$\cdot$yr^{-1}, respectively. Uplift rates ranging from 0.5 to 1.5 mm$\cdot$yr^{-1} have been measured in two different large areas located north of Treviso and south of Padova, respectively, whereas higher values are restricted to the eastern sector of the Euganean Hills. The highest sinking rates are recorded in the Po Delta (see also Figure 4). Here the movement rates show a significant spatial variability, with the maximum values of up to 15 mm$\cdot$yr^{-1} measured at the delta tips.

IPTA allows also to study with very high resolution the movements occurring at local scale. A detail of the displacements at the mouth of the Tagliamento River obtained by ENVISAT scenes for the 2003-2007 period is reported in Figure 3a.

The area, where the Bibione and Lignano

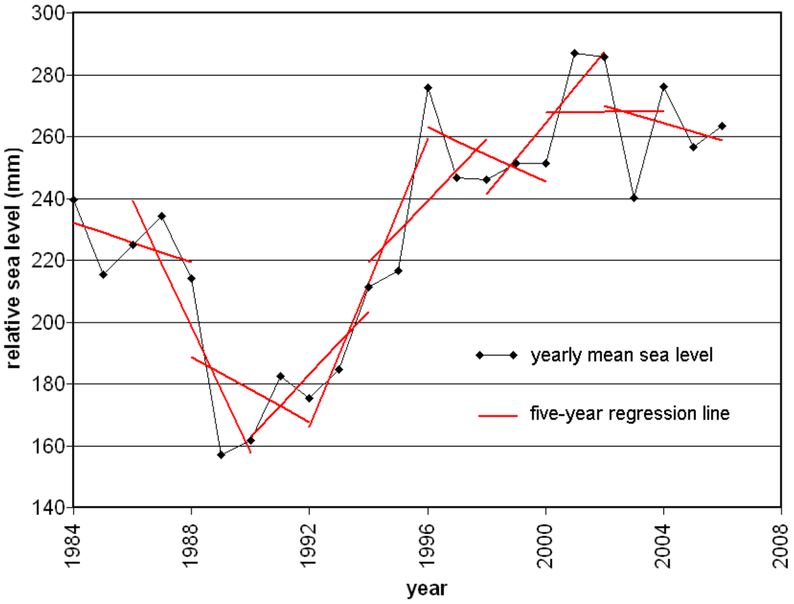

Figure 6: The yearly values of mean sea levels at Venice in the last 25 yr show a significant oscillating behaviour and contradictory tendencies.

tourist towns are located, is subsiding at a rates from 3 to 7 mm·yr^{-1}. Figure 3b shows the ground vertical movements of the Venice historical center obtained by ERS-1/2 scenes from 1992 to 2002. The city has been stable over the past decade, with the displacement rates generally smaller than 1 mm·yr^{-1} [16]. Only the eastern and, subordinately, western and northern tips of the urban area, which coincide with the city sectors built up after 1500 and where soil consolidation process may still be continuing [15], have subsided at a rate on the order of 1-2 mm/year. We used TerraSAR-X with the aim to reveal the impact of the mobile barrier works, the well known Modulo Sperimentale Elettromeccanico (Mo.S.E.), on Venice coastland stability [18]. An example of the displacements detected in 2008 at the Lido inlet is reported in Figure 3c. Consolidation related to these ongoing works is causing local settlement rates of up to 50 mm·yr^{-1}. Note that the central part of the craft harbor under construction is uniformly rising by almost 10 mm·yr^{-1} due the load of the surrounding structures and of the hydraulic overpressure acting on the lock bottom located at about 10 m below the mean sea level which is currently drained.

Investigations by the PS method have allowed to extend south of the Po Delta the mapping of the land displacements to the Ravenna area, [13, 17, 4]. Figure 4 shows the subsidence rates averaged over the 1992-2002 period. Although SAR-based measurements show that at present the mainland, e.g. the area surrounding Ravenna, appears to be substantially stable, subsidence still continues over a few kilometre wide coastal strip at a rate of about 10 mm·yr^{-1}, lesser than in the past decades, but significantly larger than the natural settlement rate. Two local portions of the littoral belt are sinking at a higher rate (up to 15 mm·yr^{-1}), probably due to gas removal from deep reservoirs located below the coastline.

It is worth reminding that researches recently performed have shown that some portions of the reclaimed farmland bounding the Venice, Po Delta and Comacchio lagoons are sinking up to 20-30 mm·yr^{-1} because of either peat soil oxidation, occurring in response of drainage for agricultural purposes, and salinisation of clayey sediments (e.g., [33, 34, 35]).

3.3 Eustacy

An analysis of the mean sea level records at the Adriatic stations of Trieste, Venice, and Ravenna over the period from 1896 to 2006 shows results that vary noticeably between the different areas. Although presenting short-cycle fluctuations, the historical tide-gauge data at Trieste, a city known to be stable, are characterized by a unique linear trend for the whole period, with a mean eustatic rise of 1.2 mm·yr^{-1} [32]. Contrasting, the average rising rate for the mean sea level at Venice and Ravenna is equal to 2.5 mm·yr^{-1} and 8.5 mm·yr^{-1}, respectively. The differences are due to the subsidence component of the RSLR that has affected Venice and Ravenna producing an apparent higher sea level rise (Figure 5). Unfortunately any long tide gauge series exists at the Po River delta. Nevertheless, we have performed a simulation trying to reconstruct the likely behaviour of a tide gauge located in the Po Delta by adding the SLR recorded at Trieste and the vertical land movement measured in the deltaic area, in particular at the Pila site. The subsidence time series has been derived from the available literature: from 1896 to 1950 after [25], from 1950 to 1957 after [24], from 1958 to 1967 after [27], from 1968 to 1974 after [28], and between 1975 to 2006 after [29] and [31]. The reconstructed behaviour of the Po Delta tide-gauge is shown in Figure 5.

Analyses of the Mean Sea Level (m.s.l.) clearly show that the use of short periods to derive a tendency of eustatic rise yields contradictory findings and suggests that a great caution must be taken in a “trend analysis”. It should be stressed that to identify a meaningful “sea level trend” it is necessary to use homogeneous and long time records. A time series at least 50 yr long must be used [32], as also suggested by [36]. For example, m.s.l. analysis at Venice shows a steady decrease (-0.8 mm·yr^{-1}) between 1971 and 1993, followed by a serious rise (5.5 mm·yr^{-1}) from 1994 to 2000, and a new lowering phase (-2.6 mm·yr^{-1}) between 2001 and 2006. As a peculiar example of the observed up-and-down behaviour, the annual m.s.l. data at Venice over the last 25 yr is reported in Figure 6 along with a few five-year regression lines. The highly oscillating behaviour clearly shows that this short period is not significant for a trend computation.

4 Environmental remarks

RSLR has been and currently appears to be the main process for the increased vulnerability of the NA coastal areas. Although nowadays the subsidence induced by subsurface fluid removal does not represent a major problem being generally under control, it has led to an irreversible loss in elevation with respect to sea level with a consequent increase of environmental hazard. The serious amount of the occurred RSLR has harmed urban zones, industrial areas, beaches, and the surrounding vast marshland reclamations which become even more prone to be submerged. A variation in the relationship between the land and the sea has occurred along the entire coast, with notable changes in geomorphologic and ecological features including coastal erosion and regression concurrently with the deepening of the sea bottom slope near the shoreline (e.g., [37]), increased flooding and coastal inundations, and damage to coastal infrastructure. In the Po Delta the morpho-ecological setting of the territory was completely altered. Changes occurred in the hydrographic net with the inversion of the original discharge direction thus requiring restoration works. A noteworthy saltwater intrusion in shallow aquifers and surficial waters has occurred along the coast (e.g., [35]). Some areas have become brackish swamps with severe consequences on the ecological system. Soil contamination by saltwater has produced detrimental consequences on the agricultural and fishing activities, which are normally located in transitional zones.

In the Venetian area, the RSLR of modest figure with respect to other areas (about 250 mm from the beginning of 1900 until today) has become of crucial importance for Venice emerging today only 900 mm above the NA [38]. Presently, relative sea level rise has increased the flood frequency by more than seven times with severe damages to the valuable urban heritage, enhanced erosion processes within the lagoon, and worsened the precariousness of the coastal strip, and ever more frequent restorative interventions are carried out.

One can say that the entire NA low coast is already experiencing the effects of the expected variation in climatic conditions, associated with the risk of a global rise in sea level. Even if land subsidence is generally no longer a major threat, further few centimetres of relative rising of the sea could be a serious peril for the survival of these coastal zones. During the 21st century, sea level is expected to rise considerably faster that in the20th, but because of uncertainties in the climate forecasting, it is not clear how rapidly this will occur. In particular, uncontroversial projections for the Adriatic Sea, that assumes very peculiar and different characteristics due to its shape and low depth, are still not available.

Reasonable forecasts of possible RSLR during this century are of paramount importance for the survival of the NA coastland and the development of effective mitigation strategies. For example, concerning the operational efficiency of Mo.S.E. at the Venice lagoon inlets, [32] propose plausible local scenarios of RLSR over the next century at Venice considering the regional subsidence history, the recorded sea level trend, along with the IPCC A1B mid-range. The results show that RSLR projections by 2100 give a large range from 170 to 530 mm, i.e. between a moderate nuisance to an unsustainable aggression. In fact the flooding events requiring the inlet closure could increase to 20 or even 250 times per year with respect to the present annual frequency of 4 times.

5 Conclusive discussion

SAR-based interferometry has opened new perspectives for studying ground surface dynamics, allowing for high resolution investigation on large areas. PSI has been applied on the NA coastland between Ravenna and the Tagliamento River over the last two decades. Once calibrated and validated by levelling and GPS measurements, this remotely-sensed technique has provided very interesting results both at “regional” and “local” (few km^2) scales. Recent (1992-2002) and present (2003-2009) maps of land vertical movements highlight a significant spatial variability with displacement rates ranging from a slight (1-2 mm$\cdot$yr^{-1}) uplift to a serious coastal subsidence of more than 15 mm$\cdot$yr^{-1}. These considerations hold for the entire NA coast. In general, differential consolidation of the Pleistocene and Holocene deposits and tectonics, and subsurface fluid withdrawals, land reclamation, and locally farmland conversion into urban areas, superimpose to produce the observed displacements.

A very detailed analysis performed over the Venetian region distinguishes the displacement components on the basis of the depth of their occurrence [40]. Deep causes, acting at a depth generally greater than 400-600 m below m.s.l., refer to downward movements of the pre-Quaternary basement and land uplift (up to 2 mm$\cdot$yr^{-1}) most likely related to neotectonic activity connected with the Alpine thrust belts and fault systems. Medium causes, acting at a depth between about 400 m and 50 m below m.s.l., are of both natural and anthropogenic origin. The former refers to the Medium-Late Pleistocene deposits that exhibit a larger cumulative thickness of clayey compressible layers at the lagoon extremities with respect to the central lagoon area where stiffer sandy formations prevail. Land subsidence due to aquifer exploitation mainly occurs in the north-eastern sector of the coastland where thousands of active wells are located. In a 10-15 km wide coastal strip the thickness, texture, and sedimentation environment of the Holocene deposits [41, 42, 43] play a significant role in controlling shallow causes of land subsidence. Other factors that contribute in increasing land sinking at a lesser areal extent are the salinization of clay deposits due to saltwater intrusion, and the biochemical oxidation of outcropping peat soils (e.g., [33, 34]). The load of buildings and structures after the conversion of farmland into urbanized areas causes superficial compaction of very local sites.

The counterpart to the land movements, as stated above, is the evolution of the m.s.l. In the study area, an heritage of secular tide-gauge data is available at Venice, Trieste, and Ravenna. Their comparison, also including the series reconstructed for the Po Delta area, is precious. Since Trieste is located on a stable area, the rate of 1.2 mm$\cdot$yr^{-1} is attributable to the eustatic rise only [32]. This value agrees with the eustatic rise measured at other stations in the Mediterranean Sea [44]. Moreover, considering the shape of the Adriatic Sea and the location of the tide gauges, it is plausible to assume as true the trend in Trieste, and apparent those of the other places (see Figure 5). In fact in Venice, Po Delta, and Ravenna the influence of land subsidence on the relative sea/ground elevation changes results equal to 57%, 95%, and 85%, respectively (Figure 7).

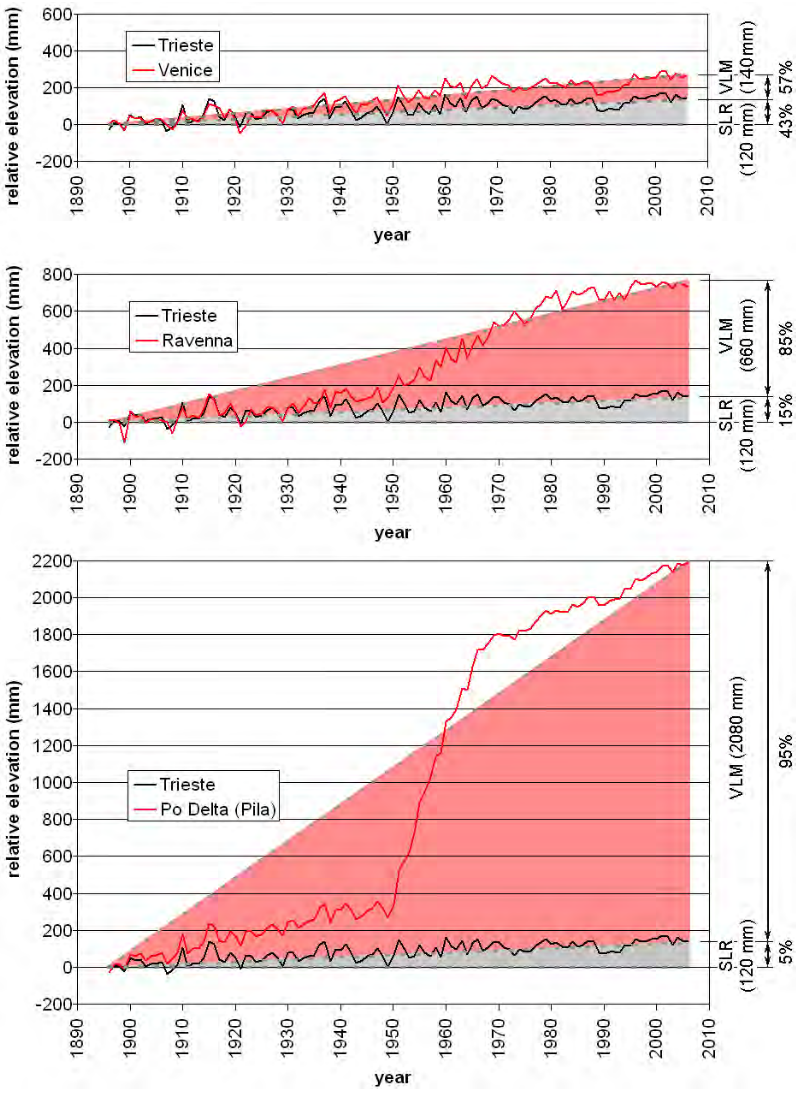

Figure 7: Yearly average sea level at Venice, Po Delta, and Ravenna compared with that of Trieste over the period between 1896 and 2006. At Venice, Po Delta, and Ravenna the contribution of land subsidence (VLM) to the overall RSLR is separated from the contribution due to the eustatic sea level rise (SLR) using the tide gauge records at Trieste (updated after [39]).

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